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Hydrologic Response for a High-Elevation Storm in the South Dakota Black Hills

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(Section on hydrologic response and context)

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ABSTRACT

A group of thunderstorms produced >4 in of rain during four periods of progressively more intense rainfall across a small part of a relatively high-elevation area of the northern Black Hills on 5 August 2014. The resulting hydrologic response was noteworthy in two very small headwater drainage basins, where the measured peak flows are by far the largest—relative to drainage area—ever documented for the high-elevation Limestone Plateau area. However, peak flows attenuated quickly in a downstream direction owing to the storms tracking perpendicular to the drainage direction, moderately dry antecedent conditions, and progressive widening of the valley bottoms.

1. Introduction

Heavy rainfall occurred across the northern Black Hills of western South Dakota during the afternoon and early evening of 5 August 2014 as a series of thunderstorms moved over the same general area (Fig. 1). Rainfall totals within this area (refer to section 2) generally exceeded the 3-h storm total of about 4 in for a 200-yr recurrence interval for the northern Black Hills (NOAA 2013).

The storm resulted in a peak flow of 91 ft^3 s^{-1} (cfs hereafter) at United States Geological Survey (USGS) stream gage 06430770 (Fig. 2a), which is located along Spearfish Creek (Fig. 3). This flow is within 50% of the largest flow of record for this site [USGS (2014); this is the source for all streamflow data within this article]. However, much larger peak flows occurred farther upstream in two small tributaries to Spearfish Creek (Keough Draw and Ward Draw, collectively centered around point "D" in Fig. 3), as documented later in section 4. Relative to drainage area, the peak flows for Keough and Ward Draws are the largest documented to date for a similar hydrogeologic setting for the Black Hills area. Thus, the National Weather Service (NWS) and USGS cooperated in documenting rainfall conditions and the resulting hydrologic response in the vicinity of the heaviest rainfall.

2. Rainfall information and meteorological setup

Rainfall totals and intensities were estimated from a combination of reports from observers (Table 1) and from the Weather Surveillance Radar-1988 Doppler (WSR-88D) located just north of New Underwood, South Dakota (KUDX), in Pennington County (Fig. 1). The rainfall occurred in four primary episodes of about 30-min duration beginning around 130 pm MDT (all times hereafter in MDT unless stated otherwise) that were progressively more intense (Fig. 4); the final burst was followed by a sharp decline in rainfall rates and then a 3-h period of much lighter "stratiform" rain (refer to the loop in Fig. 1). This rainfall occurred over a relatively high-elevation (~6000–7000 ft) area of the northern Black Hills (Fig. 3, centered on point "D"), with similar occurrences documented in Driscoll et al. (2010; see their Fig. 16). Correspondingly, there was a lagged response that began at about 230 pm at stream gage 06430770 (e.g., compare Fig. 2a to Fig. 4).

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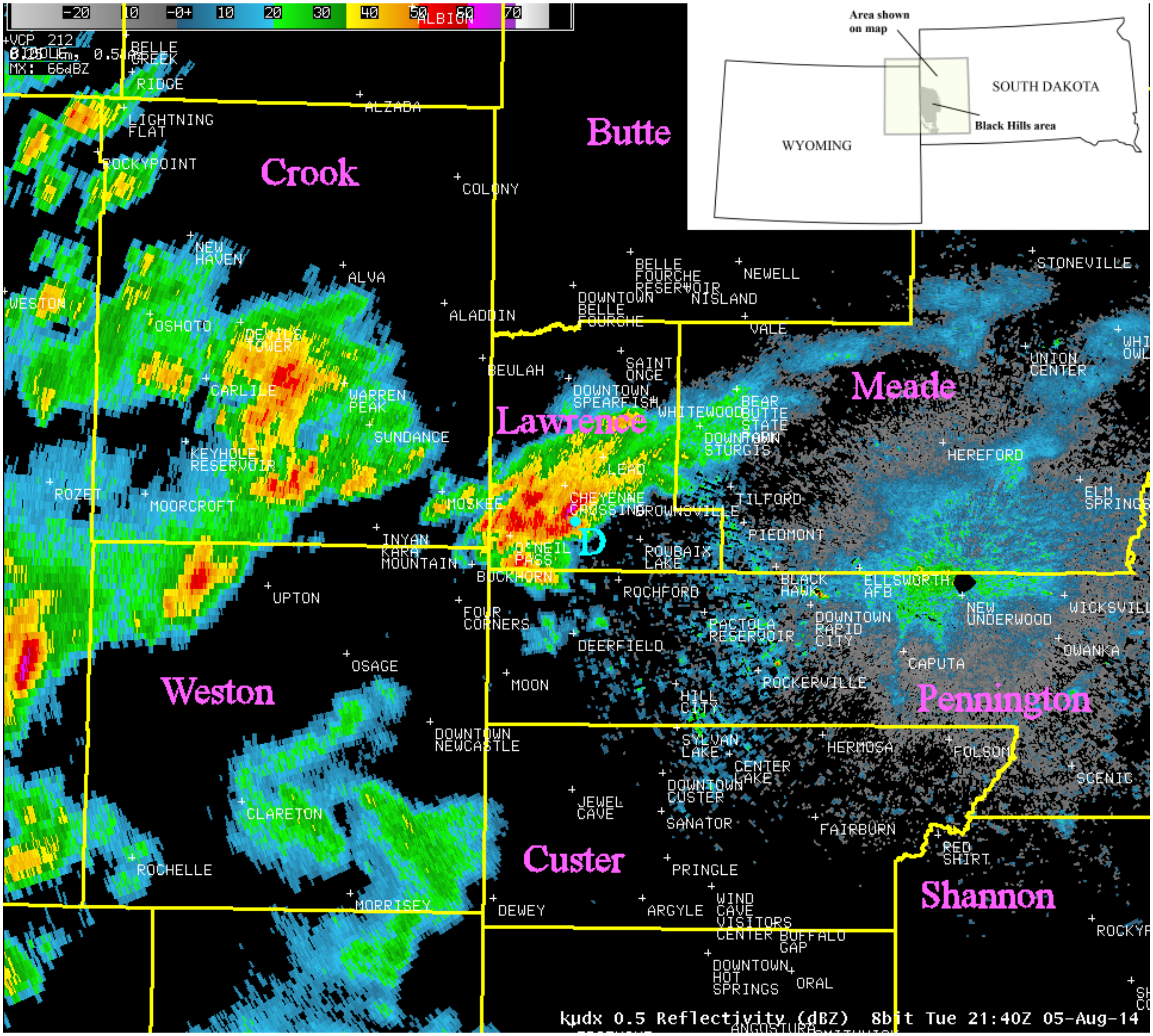


Figure 1. The 0.5° radar reflectivity from the Weather Service Radar-1988 Doppler (WSR-88D) just north of New Underwood, SD (KUDX), at 340 pm MDT (2140 UTC) 5 August 2014 near the time of the heaviest rainfall over the northern Black Hills (refer to the cyan "D" in Lawrence County for the area of interest). Towns are indicated by white plus signs, county names are in purple, and county lines are in yellow. Reflectivity (dBZ) is given per the scale at upper left. *Click the image for an external animation from 1209 pm MDT to 859 pm MDT.*

The KUDX radar estimated maximum rainfall of 6.07 in (Fig. 5a) and 5.61 in (Fig. 5b) depending upon what type of reflectivity–rainfall relationship was used. The heaviest rainfall was estimated to the south of Terry Peak by about 5 mi. These radar estimates can be in error because of an imperfect relationship between rainfall and reflectivity, as well as limitations of the radar sampling volume. Indeed, rainfall observations collected by the Rapid City NWS and USGS (Table 1) indicate that the maximum radar estimates may be high; the maximum measured rainfall was only 4.5 in (Fig. 6). In this case the radar estimate may have been high due to hail contamination. However, it is possible that the limited observation network failed to capture the maximum rainfall from this event. Nevertheless, the location of the heaviest rainfall appears to be quite similar between the observed and radar-derived values (cf. Fig. 5).

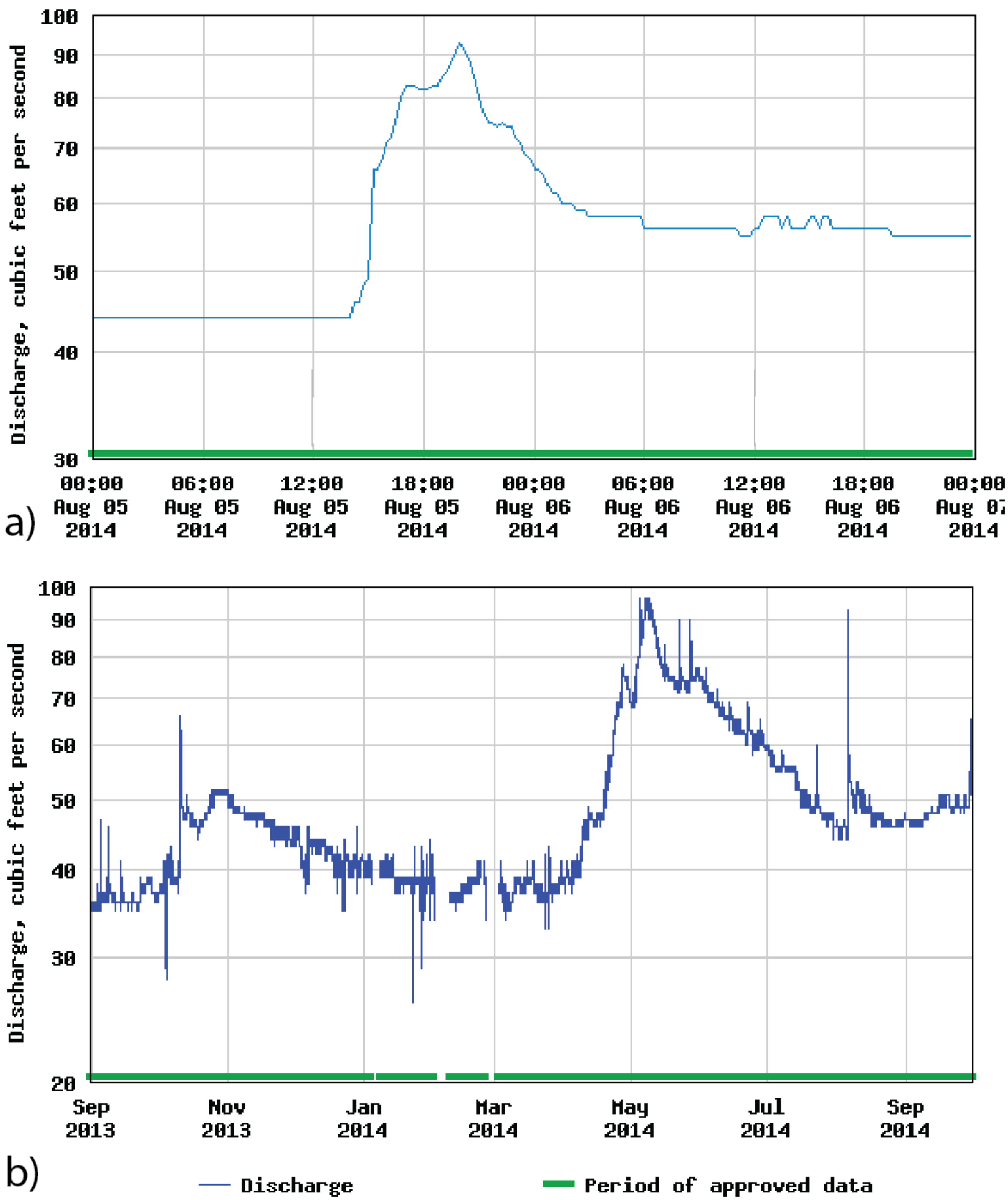


Figure 2. Hydrographs for USGS stream gage 06430770, Spearfish Creek near Lead, SD: (a) short-term hydrograph showing hydrologic response for 5–6 August 2014; and (b) longer-term hydrograph for 1 September 2013 through September 30 2014. *Click image for an external version; this applies to all figures hereafter.*

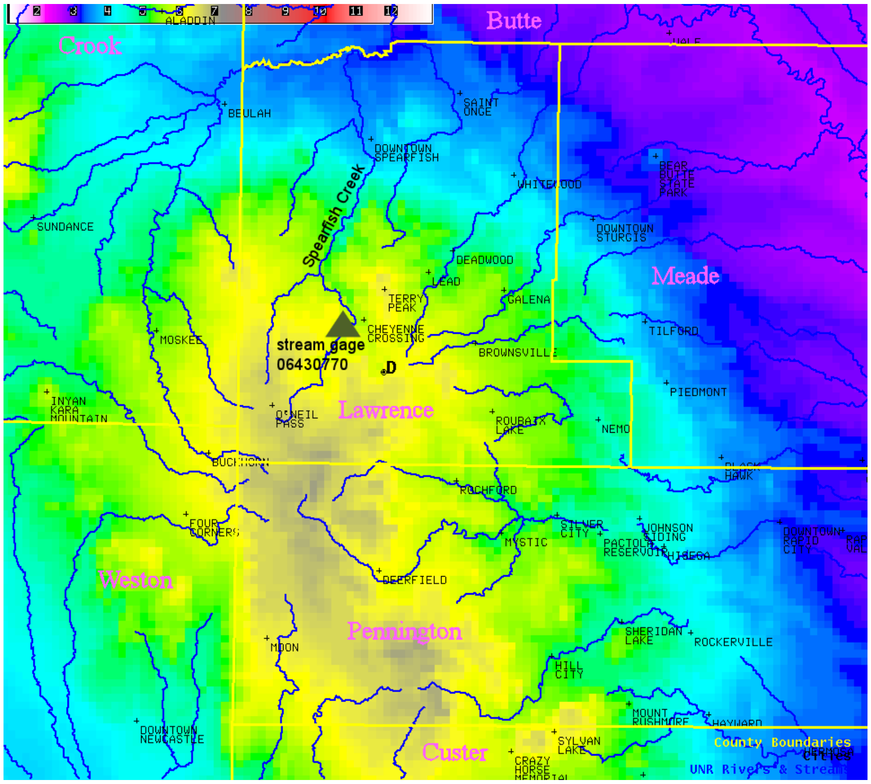


Figure 3. Major streams and topography for the northern Black Hills area with the location of interest indicated by a black "D" in Lawrence County and stream gage given by the gray filled triangle. Elevation (kft) is given per the scale at upper left. Major streams are indicated by the blue lines, towns are in black, county names are in purple, and county lines are in yellow.

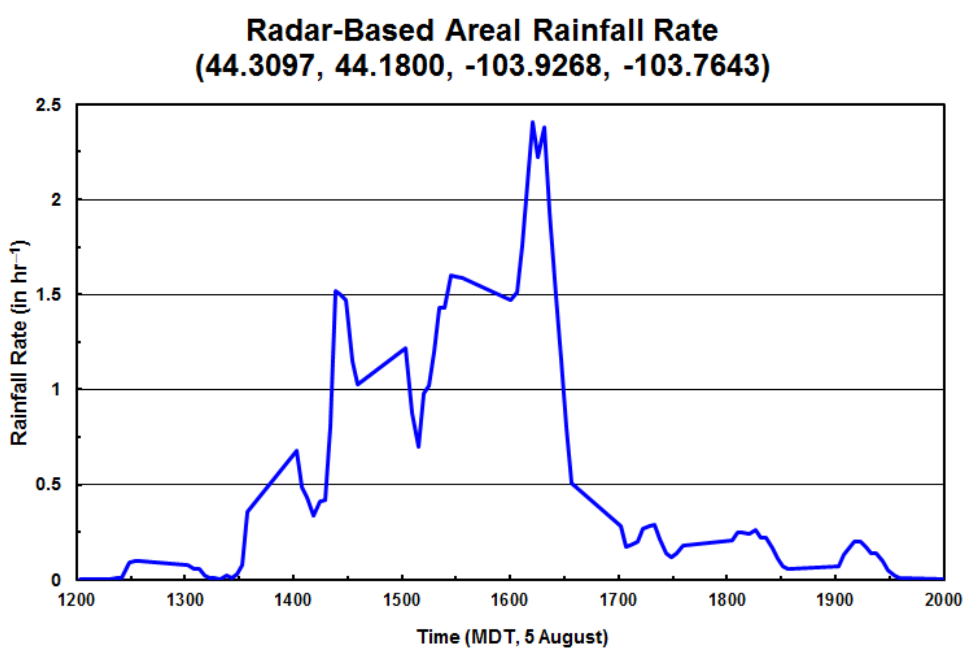


Figure 4. Dual-polarization radar-based rainfall rate estimates for an area centered on the point "D" in Fig. 1, and based on KUDX from 1203 pm MDT to 800 pm MDT 5 August 2014. The area is roughly 9 mi × 9 mi.

Table 1. Rainfall reports across Lawrence County, SD, for the 5 August 2014 heavy rainfall event. CoCoRaHS refers to the Community Collaborative Rain, Hail, and Snow network (www.cocorahs.org/), RAWS refers to Remote Automatic Weather Stations operated by the United States Forest Service (raws.fam.nwcg.gov/), and the Public reports were gathered by the NWS.

Rainfall (in)	Latitude	Longitude	Location	Source
4.50	44.2678	–103.8135	Lead Country Club	Public
3.95	44.2781	–103.8092	Lead 5.5 SSW	CoCoRaHS
3.50	44.2979	–103.8673	Cheyenne Crossing	Public
3.25	44.3158	–103.8878	Cheyenne Crossing 1.5 NW	Public
2.30	44.2324	–103.7761	Dumont	Public
2.00	44.2370	–103.8026	Cheyenne Crossing 5 SE	Public
1.99	44.1900	–103.5106	Nemo RAWS	RAWS
1.82	44.3269	–103.8939	Annie Creek near Lead	USGS Stream Gage
1.70	44.3686	–103.7653	Central City	USGS Stream Gage
1.00	44.1500	–103.5000	Nemo 3 S	Public
0.90	44.2947	–103.5964	Elk Creek nr Roubaix	USGS Stream Gage
0.64	44.4422	–103.6289	Whitewood Creek	USGS Stream Gage
0.60	44.3927	–103.7952	Lead 3.1 NNW	CoCoRaHS
0.54	44.5179	–103.6698	Whitewood 4.2 NNW	CoCoRaHS
0.45	44.4836	–103.8208	Spearfish 1.3 ESE	CoCoRaHS
0.42	44.4882	–103.8493	Spearfish 0.1 WSW	CoCoRaHS
0.29	44.4407	–103.8052	Spearfish 3.9 SSE	CoCoRaHS

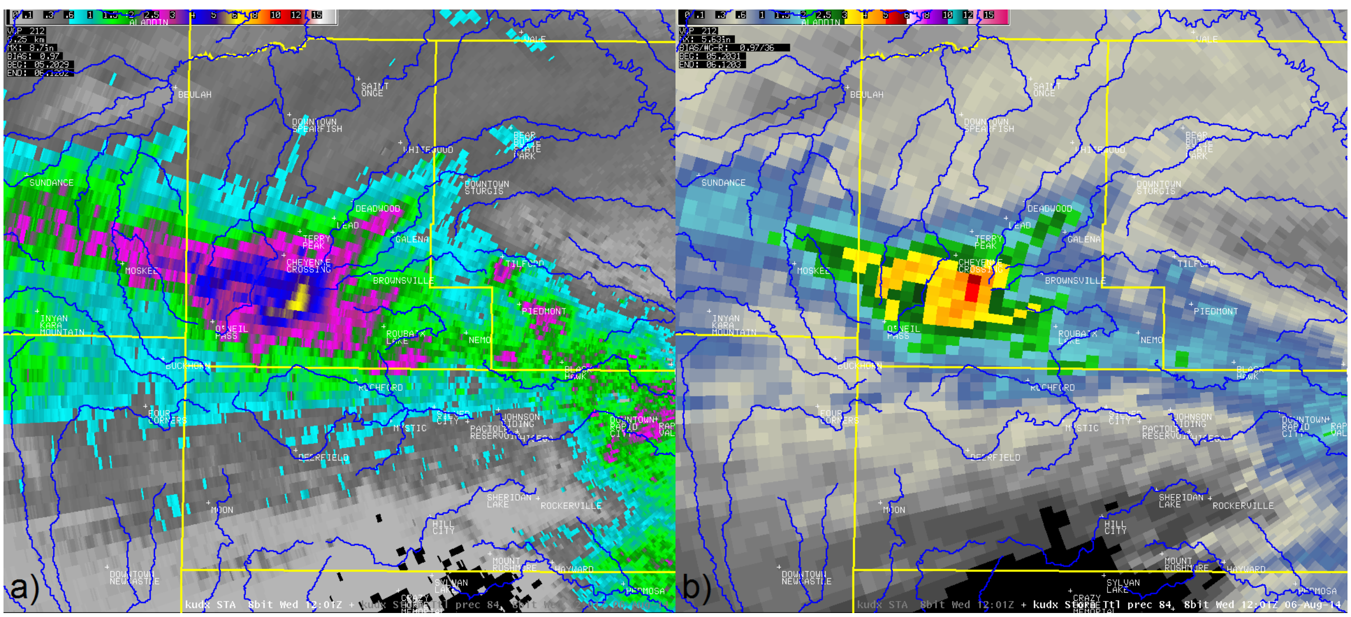


Figure 5. (a) Radar-derived storm-total precipitation (in, scale at upper left) from 230 pm MDT 5 August to 600 am MDT 6 August 2014 using the KUDX WSR-88D dual-polarization algorithm. Major streams are indicated by the blue lines, towns are in white, and county lines are in yellow. (b) Same as (a) except for the "legacy" (i.e., pre dual-polarization) precipitation algorithm (Crum et al. 1993).

In order to account for the limitations of the radar (e.g., overestimation) as well as limitations of the observations (e.g., under-sampling), the radar-derived rainfall estimates can be bias-corrected by using the observed precipitation reports. This is done daily by the NWS River Forecast Centers, with the output

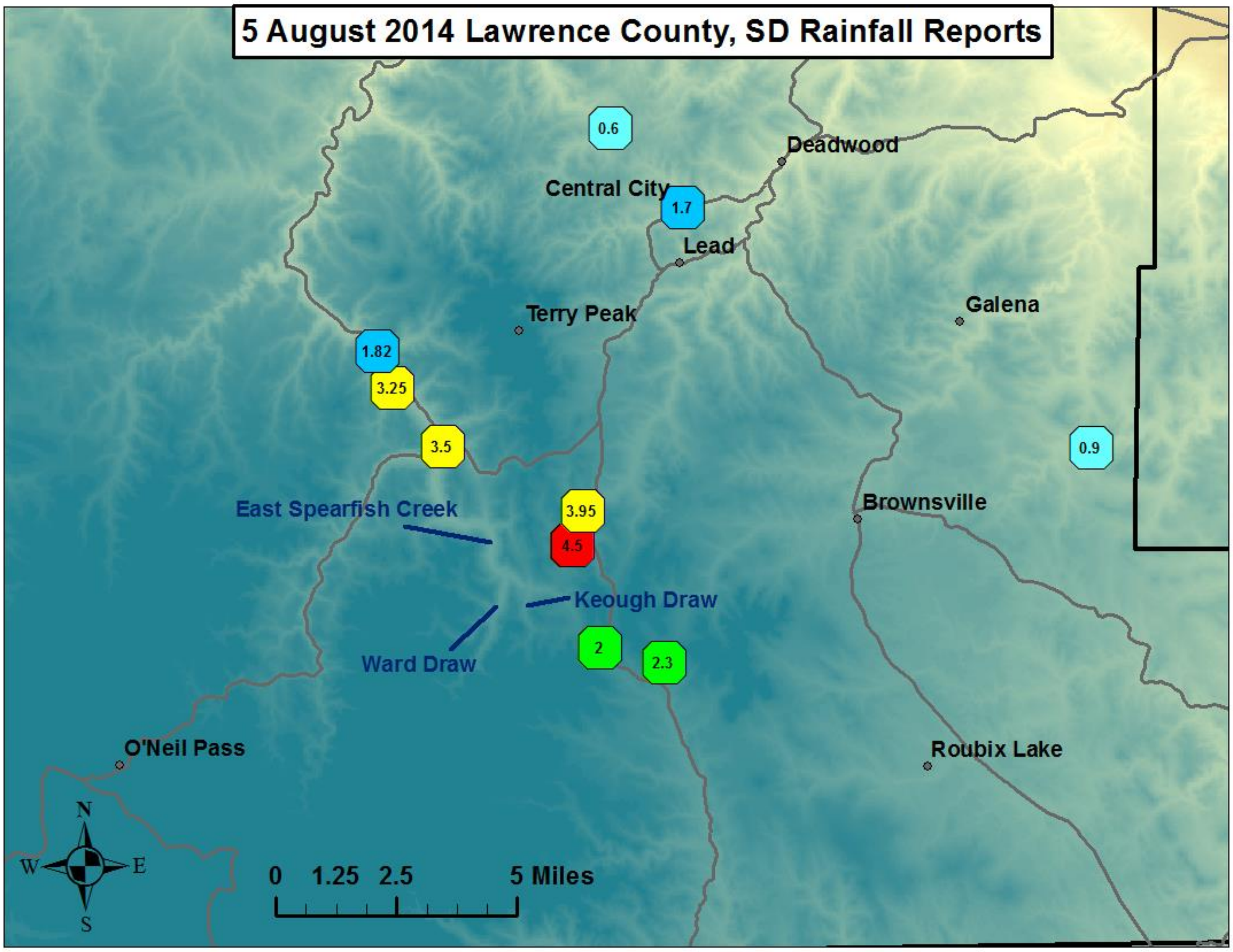


Figure 6. Observed rainfall reports from 5 August 2014 across Lawrence County in the northern Black Hills. The county line is given with the medium thickness black line and the major roads are given by the thinner gray lines. Topography is shaded with higher elevations corresponding to the blue colors.

interpolated to a 2.5 mi × 2.5 mi (4 km × 4 km) polar-stereographic grid (Lin and Mitchell 2005). This results in a smoothed display that gives a better indication of the true rainfall distribution rather than just using the radar or spotter reports alone. Based on this analysis (Fig. 7), a maximum unsmoothed gridded value of 4.15 in was given for the area south of Terry Peak—where the point maximum value of 4.5 in was reported. The 4.15-in rainfall total is approximately equal to the 3-h, 200-yr recurrence interval precipitation estimate in this area (4.29 in; NOAA 2013). Referring back to the topography (Fig. 3) and the streams (Fig. 7)—both of which indicate stream orientations toward the northeast—much of the heaviest rain fell along an axis that is perpendicular to the streams of the northern Black Hills. This hydrological setup is less favorable for flash flooding than down-basin storm motion, which is most favorable.

The heavy rainfall was favored by a very moist atmosphere on 5 August 2014. Early morning observations (Fig. 8a, 6 am) indicated 1.41 in of precipitable water at Rapid City, South Dakota, which is 160% of the long-term average and 2.2σ above normal. By 6 pm the precipitable water had increased to 179% and 2.9σ (Fig. 8b). The corresponding 6 pm sounding from Rapid City (Fig. 9) exhibited a modest amount of buoyancy (~1000 J kg^{-1}) and very moist conditions throughout the troposphere (similar to the 6 am sounding). The heavy rain-producing storms remained upstream of the late-afternoon sounding prior to its release, and thus this sounding is deemed

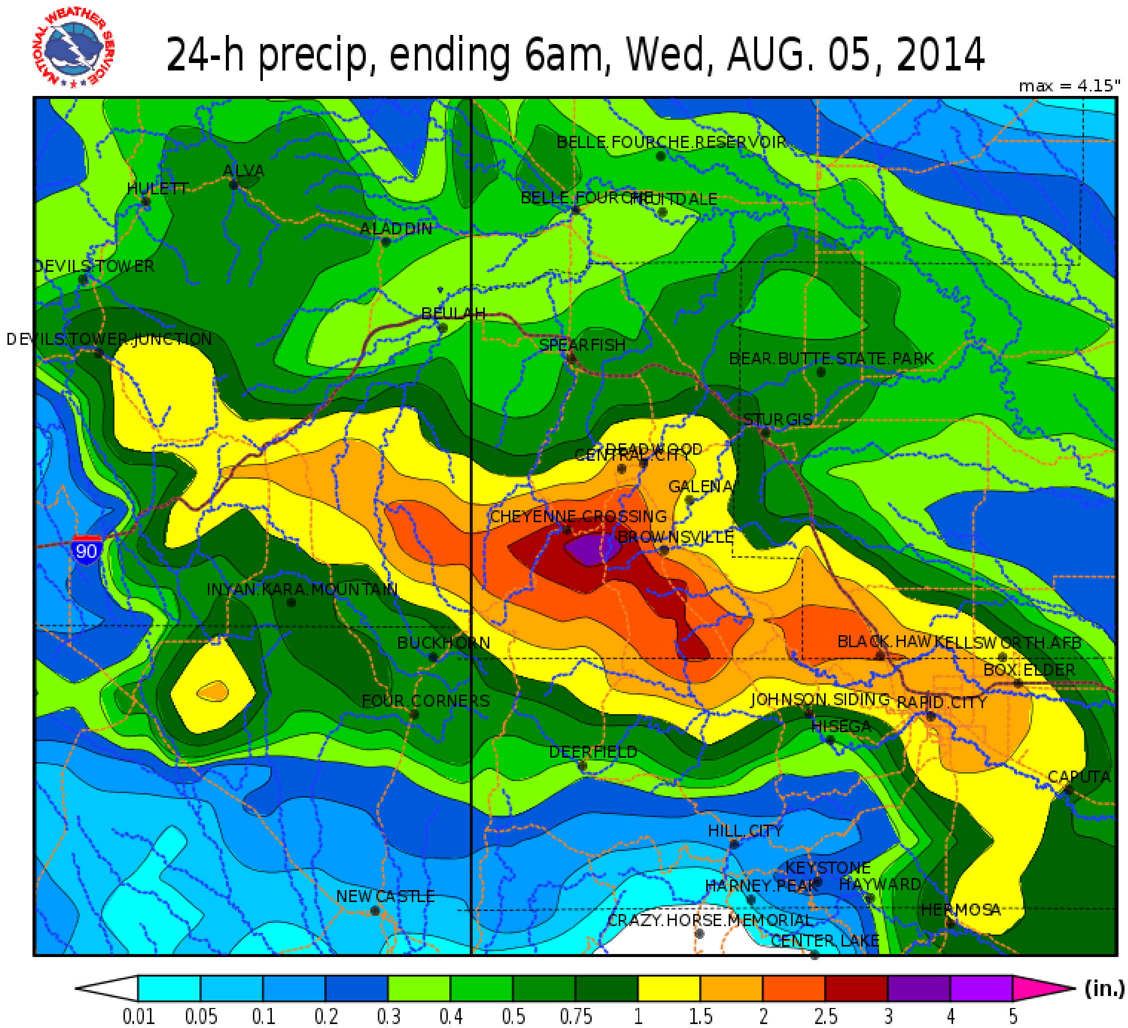


Figure 7. Bias-corrected radar-derived rainfall (i.e., stage IV; Lin and Mitchell 2005) produced by the NWS River Forecast Center in Kansas City, MO, for the 24-h period ending at 6 am MDT 6 August 2014. Slight smoothing has been applied, thus the maximum gridded value (4.15 in) is slightly larger than the displayed maximum in the image. State boundaries are depicted by thick black lines; county lines are dashed black lines; major roads are dashed brown lines; major streams are dashed blue lines; and points of interest and towns are noted with black circles and labelling. This figure was produced with the Grid Analysis and Display System (GrADS; iges.org/grads/) developed by the Center for Ocean–Land–Atmosphere Studies (COLA).

representative of the inflow environment of the northern Black Hills storms (although some convective contamination is suggested in the midlevels from 650–450 mb).

3. Antecedent conditions

Antecedent conditions can affect the generation of runoff; moist conditions tend to favor higher runoff than dry conditions—all else being equal. Figure 2b provides a good perspective on antecedent conditions, which were heavily influenced by an exceptionally heavy snowstorm that occurred on 4–5 October 2013 (Edwards et al 2014) and supplied abundant moisture that was slowly dissipated over the course of subsequent months. The hydrograph rise that started about 1 April 2014 included surplus moisture from the October 2013 storm, melting of subsequent winter snowfall, and additional moisture from rain falling on the saturated watershed. The peak flow of 97 cfs for water year 2014 (1 October 2013 through 30 September 2014) for stream gage 06430770 occurred on 5 May 2014, with similar daily maxima occurring through 9 May 2014. About one-half of the instantaneous peak flow of 91 cfs for 5 August 2014 consisted of base flow.

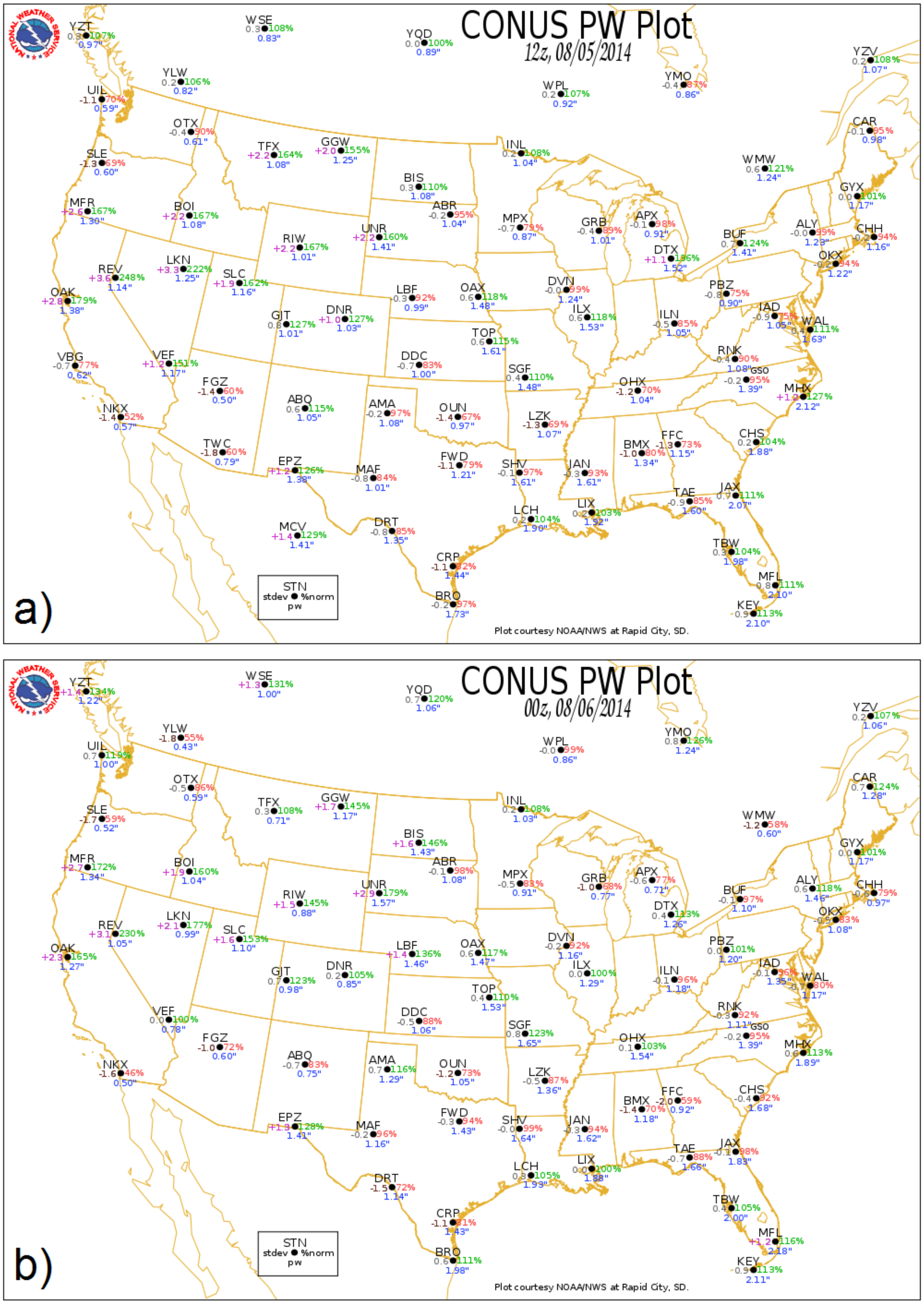


Figure 8. (a) Surface-to-300-mb precipitable water (in) for 6 am (or 1200 UTC) 5 August 2014. Station legend is given at the lower left. Refer to www.crh.noaa.gov/unr/?n=pw for information on the climatology used for these charts. (b) as in (a) but for 6 pm 5 August 2014 (or 0000 UTC 6 August 2014). These figures were produced with GrADS (iges.org/grads/).

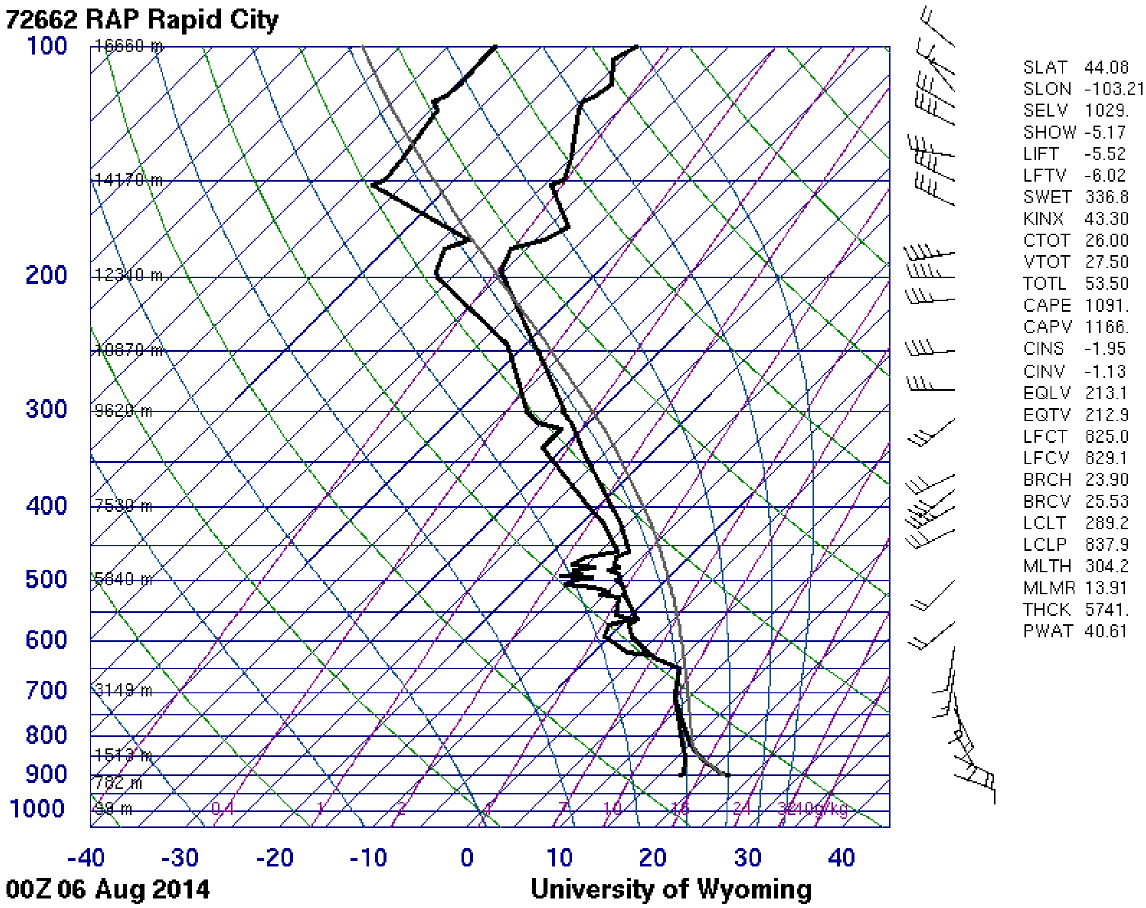


Figure 9. Observed skew*T*–log*p* thermodynamic diagram for Rapid City, SD (UNR), valid 6 pm MDT 5 August 2014 (or 0000 UTC 6 August 2014). The abscissa is temperature (°C) and the ordinate is pressure (mb) at the indicated elevation above sea level. The horizontal wind is given by half-barbs (5 kt) and full barbs (10 kt). Image courtesy of the University of Wyoming (weather.uwyo.edu/upperair/sounding.html).

Dissipation of the earlier surplus moisture apparently began slowing after the hydrograph crest of 5–9 May (Fig. 2b). During May 2014, rainfall across southwestern Lawrence County was normal to about 0.5–2.0 in below normal (Fig. 10a), which further contributed to a prolonged hydrograph recession that continued until the 5 August storm occurred. This prolonged recession apparently was driven primarily by long-term conditions, with minimal effects from wetter than normal conditions during June (rainfall surpluses of 0.5–3.0 in; Fig. 10b) and drier than normal conditions during July (0.5–2.0 in below average; Fig. 10c).

Another indicator of antecedent moisture comes from various drought indices. One of these indices, soil moisture anomaly, indicated that the ground was modestly wet across the Black Hills area at the end of July (Fig. 11). In support of this, the Palmer drought severity index indicated "extremely moist" conditions (Fig. 12). These two drought measures take into account multiple months as opposed to just the most recent month. In total, Figs. 10–12 indicate that there were moist conditions over a long-term perspective, but some short-term dryness was evident. Consistent with this, the Rapid City NWS issued a flood advisory (but not a flash flood warning) because of the heavy rainfall across Lawrence County, and very few public impacts were noted.

4. Hydrologic response and context

a. Hydrologic response for Keough Draw and Ward Draw

The hydrologic response to the 5 August 2014 rainfall was most noteworthy in Keough Draw and Ward Draw, which are small tributaries to East Spearfish Creek (Figs. 6 and 13). Following a citizen report of unusual high-flow evidence in these remote

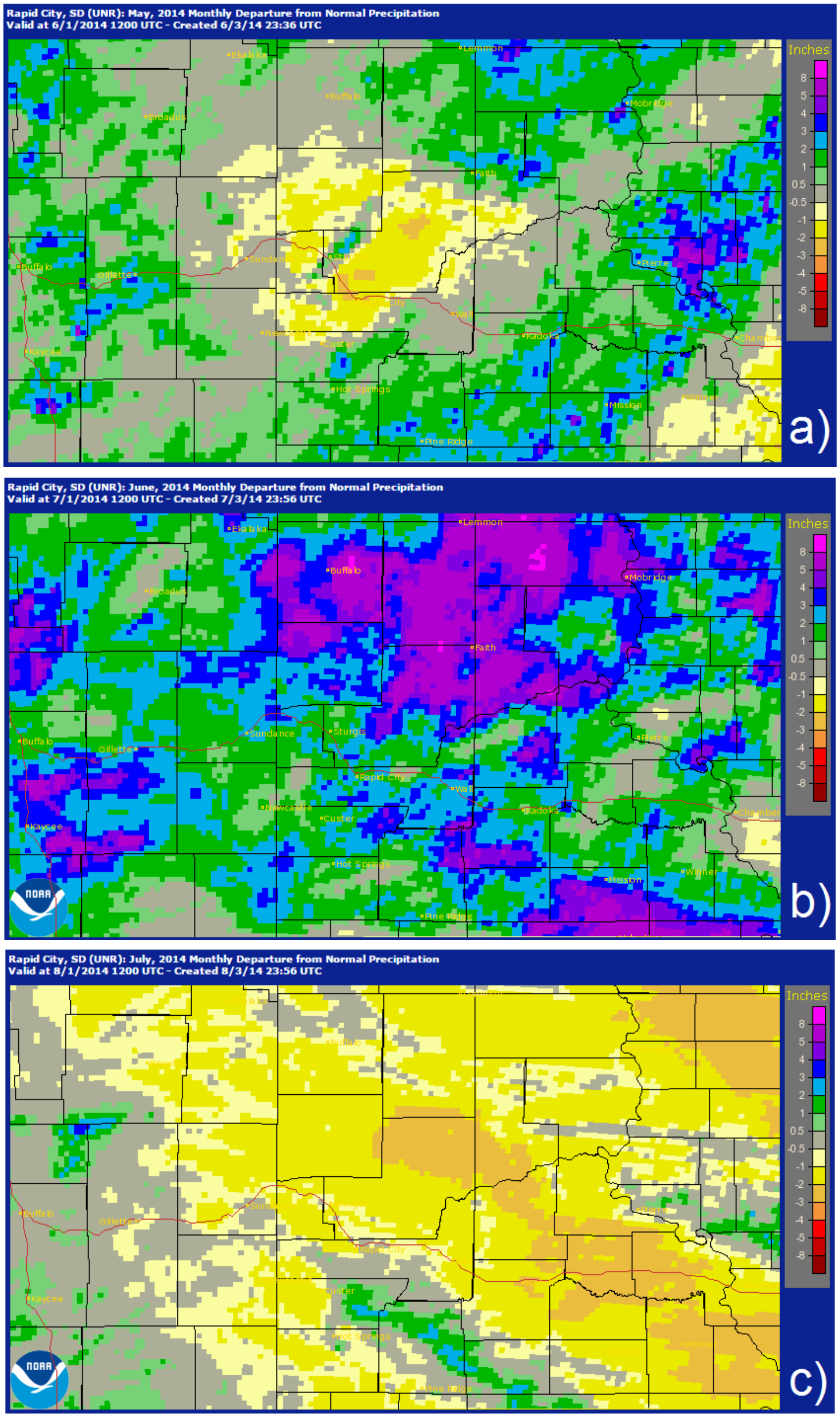


Figure 10. (a) Departure of normal precipitation in May 2014 for northeastern WY and western SD. (b) Same as (a) except for June 2014. (c) Same as (a) except for July 2014. Images provided by the NWS (water.weather.gov/precip/).

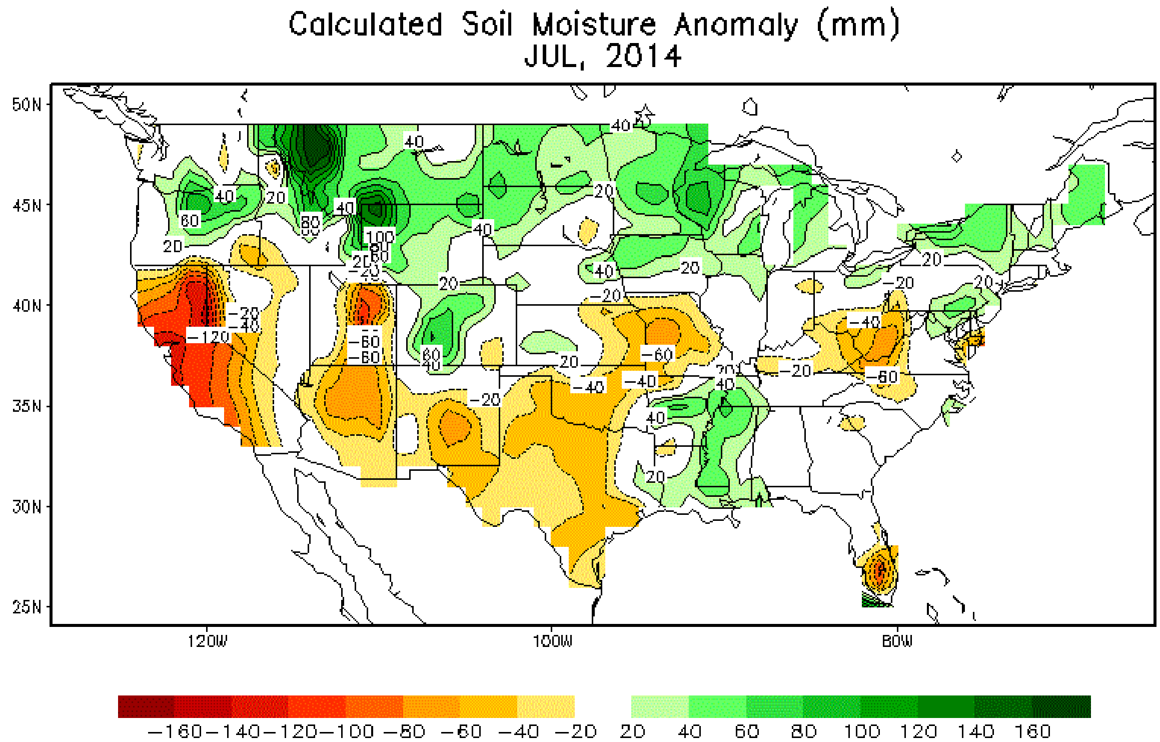


Figure 11. Calculated soil moisture anomaly for July 2014. Image courtesy of the Climate Prediction Center (www.cpc.ncep.noaa.gov/).

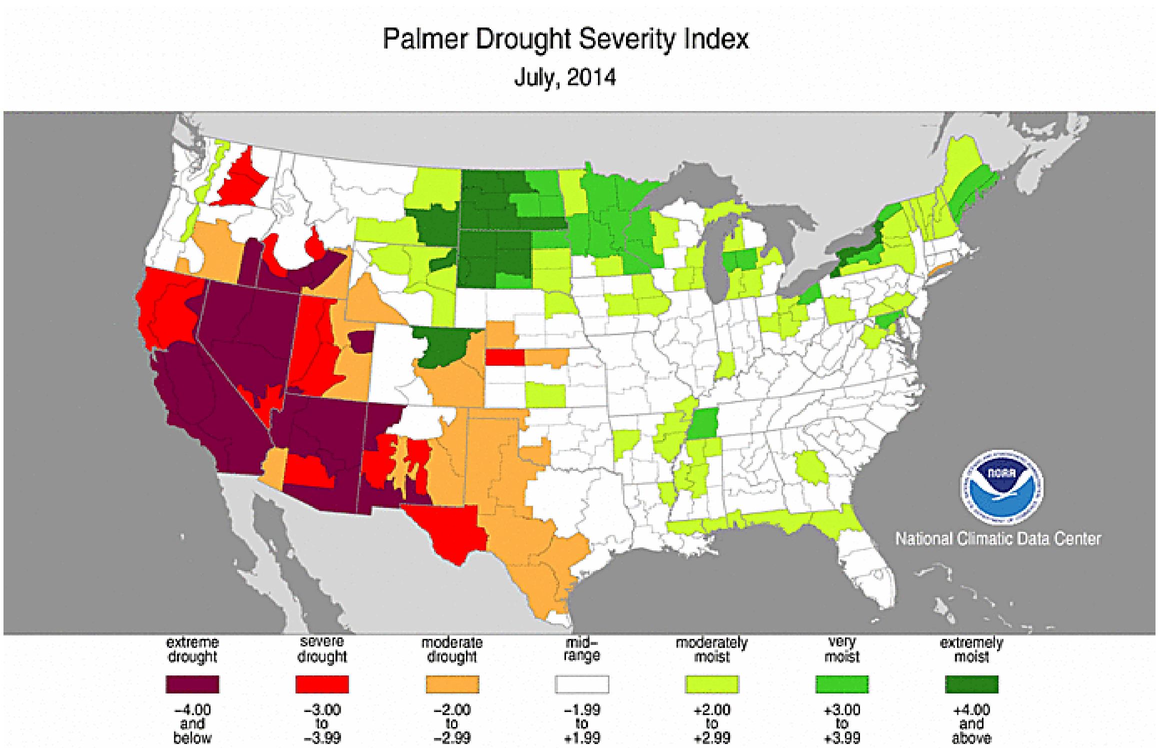


Figure 12. Palmer drought severity index for July 2014. Image courtesy of the National Climatic Data Center (www.ncdc.noaa.gov/).

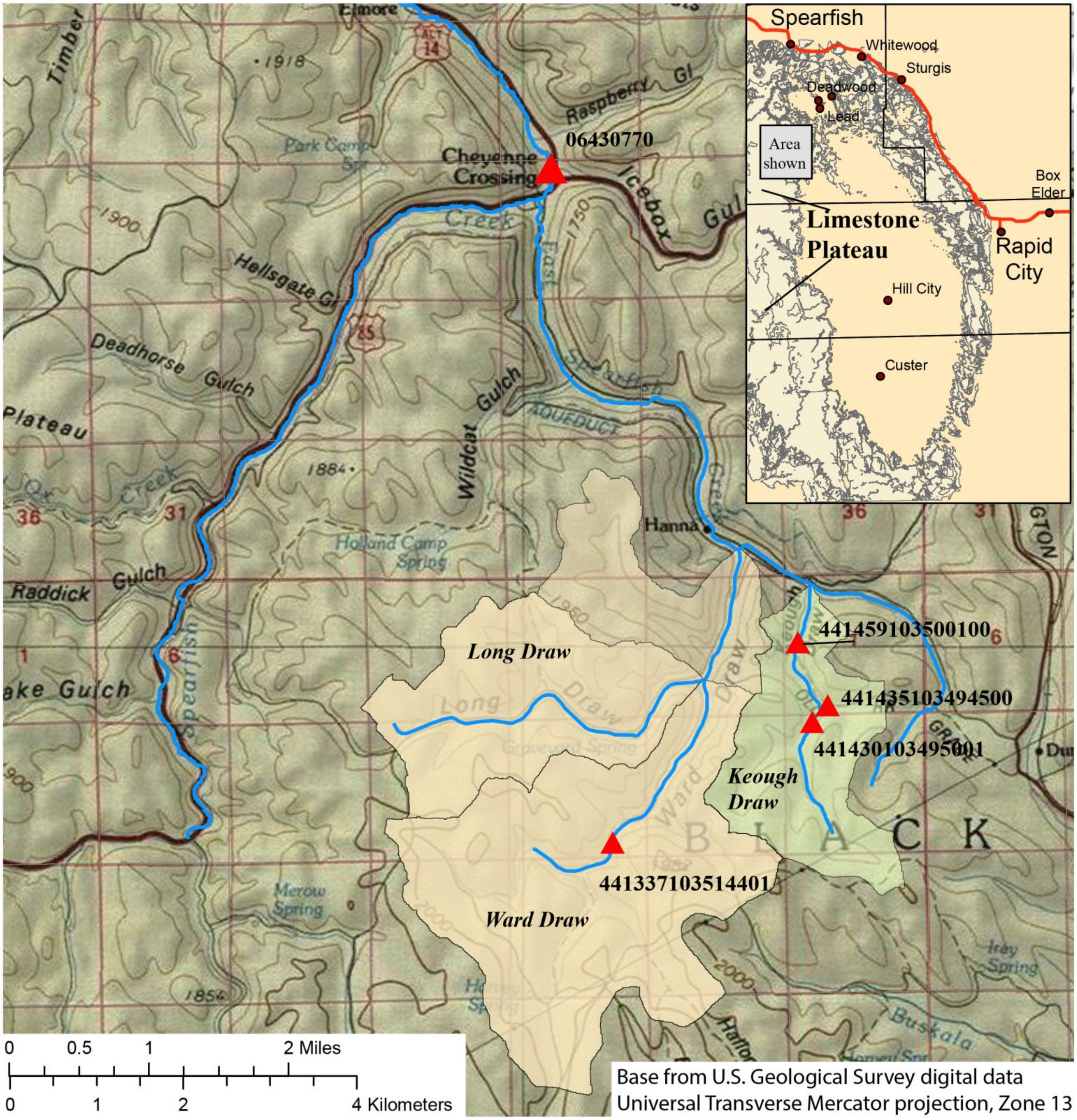


Figure 13. Locations of peak-flow measurement sites (small red-filled triangles) in Keough Draw and Ward Draw.

drainages, USGS staff made peak-flow determinations (based on high-water marks) to derive flow estimates at four locations, three in Keough Draw and one in Ward Draw (Table 2). Methods included slope-area determinations (Dalrymple and Benson 1967) for two sites and critical-flow estimates (Grant 1997) for two other sites. Average velocities were similar for all sites, providing confidence that the inherent assumption of critical flow was reasonable for the two sites with critical-flow estimates.

The largest peak flow was 340 cfs for site 441430103495001 in Keough Draw (Table 2), which has a drainage area of 1.0 mi^2. The smaller "east tributary," which joins Keough Draw just downstream,

Table 2. Summary of Keough Draw and Ward Draw peak-flow measurements following the 5 August 2014 rainfall event.

Site name	Site ID	Latitude	Longitude	Drainage area (mi^2)	Estimated peak flow (cfs)	Cross-section area (ft^2)	Average velocity (ft s^{-1})	Measure-ment type
Keough Draw	441430103495001	44.2413	–103.8316	1.0	340	49.6	6.9	Slope-area
East tributary to Keough Draw	441435103494500	44.2431	–103.8292	0.25	130	19.4	6.8	Critical flow
Lower Keough Draw	441459103500100	44.2496	–103.8335	1.5	220	27.7	7.9	Critical flow
Ward Draw	441337103514401	44.2291	–103.8607	2.9	160	26.4	6.1	Slope-area

produced a peak flow of 130 cfs from a drainage area of only 0.25 mi^2. About 0.5 mi farther downstream from this confluence, the peak flow attenuated to 220 cfs, despite a larger drainage area of 1.5 mi^2. Visual observations indicated further attenuation as the flood peak progressed downstream to East Spearfish Creek, clearly indicating that the rainfall intensities and amounts decreased from south to north, which is consistent with the storm footprint and associated estimates of total rainfall (Figs. 5 and 7). Attenuation was further enhanced by progressive widening of the valley bottom, which exists in the downstream direction.

A peak flow of 160 cfs from a drainage area of 2.9 mi^2 was measured for Ward Draw (Table 2), which is west of Keough Draw and also west of the area of heaviest rainfall (Figs. 5 and 7). Visual observations again indicated rapid attenuation as the peak progressed downstream, which was caused by the same factors as for Keough Draw.

Stream gage 06430770, which is located along Spearfish Creek just downstream from East Spearfish Creek, measured a rather subdued hydrologic response from a much larger drainage area (65.0 mi^2)—relative to the small headwater areas of Keough Draw and Ward Draw that are located near the area of heaviest rainfall. The hydrograph (Fig. 2a) began rising at about 230 pm, which is coincident with the second primary rainfall burst (Fig. 4). An initial rise from about 45 cfs to about 65 cfs occurred in about 1 h and may have resulted primarily from runoff from roads adjacent to Spearfish Creek and East Spearfish Creek. Spearfish Creek continued rising for about another 6 h, but attained a peak flow of only 91 cfs, which is consistent with the attenuation noted for Keough Draw and Ward Draw.

b. Context of hydrologic response

Keough Draw and Ward Draw are located along the northeastern extent of the Limestone Plateau (Figs. 13 and 14), an area in the west-central Black Hills that characteristically produces peak flows much smaller than in other surrounding areas, relative to drainage area. Sando et al. (2008) cited low topographic relief and high infiltration capacities of bedrock outcrops as hydrogeologic factors causing smaller potential for generating direct runoff, relative to other parts of the Black Hills. Driscoll et al. (2010) identified climatological factors causing smaller potential for generating exceptionally strong rain-producing thunderstorms in the higher elevations of the Black Hills, relative to lower elevations. Harden et al. (2011) and Driscoll et al. (2012) provided additional insights regarding differences in peak-flow potential between the higher and lower elevations of the Black Hills. Examination of the peak flows resulting from the 5 August 2014 storm, relative to peak-flow data for other selected stream gages, allows an opportunity to further the understanding (and future quantification) of the complex factors driving differences in peak-flow potential between higher and lower elevations.

Table 3 presents data regarding peak-flow magnitudes relative to drainage area for the Keough Draw and Ward Draw sites, and also provides comparisons with similar data for selected stream gages throughout the Black Hills area. Magnitudes of listed peak flows were "normalized" by dividing by drainage area raised to the 0.6 power. Sando et al. (2008) provided additional details on this approach, which was used in developing a regional mixed-population approach for flood-frequency analysis for the Black Hills area. This essentially provides an approach for scaling peak-flow magnitude per square mile of drainage area, as noted by the normalized flow for the Keough Draw site with a drainage area of 1.0 mi^2 (normalized value is equal to the largest peak flow).

A first grouping for comparison with the Keough Draw and Ward Draw sites includes eight high-elevation stream gages (Table 3) that are within or

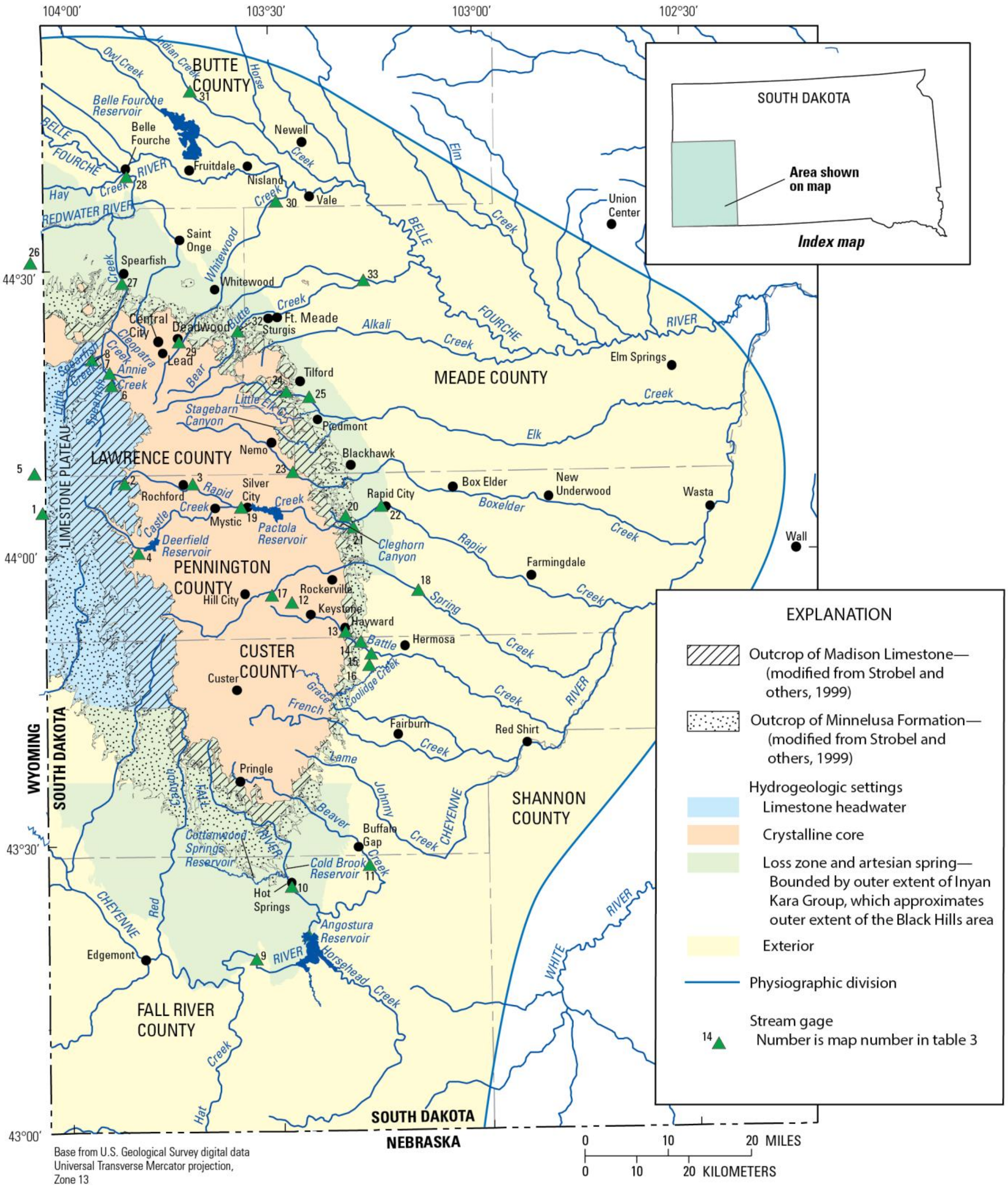


Figure 14. Location of selected USGS stream gages in the Black Hills area, relative to hydrogeologic settings. Modified from Driscoll et al. (2010).

Table 3. Peak-flow data for selected sites in the Black Hills area, for comparison with data for Keough Draw and Ward Draw. [WY = water year; LS-HW = Limestone Headwater; CC = Crystalline Core; LZ-AS = Loss Zone and Artesian Spring; EX = Exterior; and Mixed = multiple settings.]

Map number on Fig. 14	Site ID	Station name	Hydro-geologic setting[a]	Elev-ation of gage (ft)	Years of record (through WY 2013)[b]	Drain-age area (mi^2)	Largest peak flow (cfs)	Largest normalized peak flow[c]	Year of largest peak flow
Keough Draw and Ward Draw sites									
Fig. 13[d]	441430103495001	Keough Draw	LS-HW	6060	N/A	1.0	340	340	2014
Fig. 13[d]	441435103494500	East tributary to Keough Draw	LS-HW	6070	N/A	0.25	130	299	2014
Fig. 13[d]	441459103500100	Lower Keough Draw	LS-HW	5900	N/A	1.5	220	172	2014
Fig. 13[d]	441337103514401	Ward Draw	LS-HW	6155	N/A	2.9	160	84.5	2014
Selected high-elevation stream gages within or near the Limestone Plateau									
1	06392900	Beaver Creek at Mallo Camp, near Four Corners, WY	LS-HW	6030	31	10.3	154	38.0	2011
2	06408700	Rhoads Fork near Rochford, SD	LS-HW	5965	32	7.82	19	5.5	2011
3	06408850	Silver Creek near Rochford, SD	CC	5235	12 (2008)	6.24	400	133	2008
4	06409000	Castle Creek above Deerfield Reservoir near Hill City, SD	LS-HW	5920	64	79.3	1120	81.2	1952
5	06429500	Cold Springs Creek at Buckhorn, WY	LS-HW	6090	31	22.4	42	6.5	1999
6	06430770	Spearfish Creek near Lead, SD	LS-HW	5310	25	65.0	181	14.8	1998
7	06430800	Annie Creek near Lead, SD	CC	5125	25	3.73	270	123	1995
8	06430850	Little Spearfish Creek near Lead, SD	LS-HW	5020	25	27.8	215	29.2	2013
Selected sites from Driscoll et al. (2010) or Harden et al. (2011)									
9	06400500	Cheyenne River near Hot Springs, SD	EX	3191	36 (1972)	8,757	114,000	491	1920
10	06402000	Fall River at Hot Springs, SD	LZ-AS	3413	32 (1952)[e]	136	13,100	687	1938
11	06402500	Beaver Creek near Buffalo Gap, SD	Mixed	3150	76	127	11,700	640	1938
12	06403800	Battle Creek tributary near Keystone, SD	CC	4860	25 (1980)	0.65	1330	1720	1972
13	06404000	Battle Creek near Keystone, SD	CC	3800	54	58.6	26,200	2280	1972
14	435112103163700	Tributary to Deadman Gulch near Hermosa, SD	LZ-AS	3550	1	0.678	2000	2530	2007
15	435021103164900	Tributary (right bank) to Battle Creek above Hermosa, SD	LZ-AS	3500	1	0.977	3000	3040	2007
16	434858103151700	Tributary (left bank) to Grace Coolidge Creek above Hermosa, SD	LZ-AS	3460	1	0.565	2100	2960	2007
17	06406900	Palmer Creek near Hill City, SD	CC	4780	25 (1980)	13.3	4370	925	1972
18	06408500	Spring Creek near Hermosa, SD	Mixed	3265	55 (2004)	206	13,400	548	1972
19	06410500	Rapid Creek above Pactola Reservoir at Silver City, SD	CC	4620	60	202[f]	2060	85	1965

Map number on Fig. 14	Site ID	Station name	Hydro-geologic setting[a]	Elev-ation of gage (ft)	Years of record (through WY 2013)[b]	Drain-age area (mi^2)	Largest peak flow (cfs)	Largest normalized peak flow[c]	Year of largest peak flow
Selected sites from Driscoll et al. (2010) or Harden et al. (2011)—continued									
20	440325103182500	Cleghorn Canyon at Rapid City, SD	LZ-AS	3400	2	7.0	12,600	3920	1972
21	06412500	Rapid Creek above Canyon Lake near Rapid City, SD	Mixed	3398	67	54[g]	31,200	2850	1972
22	06414000	Rapid Creek at Rapid City, SD	Mixed	3230	68[h]	93[g]	50,000	3300	1972
23	06422500	Boxelder Creek near Nemo, SD	CC	4320	51	94.4	30,100	1970	1972
24	None established	Elk Creek paleoflood site (Dracula's Ledge)[i]	Mixed	4300	2000[i]	40	83,000[i]	9070	1100[i]
25	06424500	Elk Creek above Piedmont	Mixed	3800	4 (1972)	49	12,000	1160	1972
26	06429905	Sand Creek near Ranch A near Beulah, WY	Mixed	3570	32	275	1230	42	1995
27	06431500	Spearfish Creek at Spearfish, SD	Mixed	3640	68	165	5000	234	1904
28	06433000	Redwater River above Belle Fourche, SD	Mixed	3000	68	930	16,400	271	1962
29	06436170	Whitewood Creek at Deadwood, SD	CC	4500	14	40.7	3540	383	1995
30	06436198	Whitewood Creek above Vale, SD	Mixed	2840	31	102	4500	281	2008
31	06436700	Indian Creek near Arpan, SD	EX	2900	20	313	16,700	531	1976
32	06437200	Bear Butte Creek near Galena, SD	CC	3770	22	52.1	19,000	1773	1972
33	06437500	Bear Butte Creek near Sturgis, SD	EX	2780	51	181	12,700	561	1962

[a] Predominant hydrogeologic setting of drainage area, as shown in Fig. 14.
[b] Last water year of record shown in parentheses, when different than 2013.
[c] Largest normalized peak flow is calculated by dividing largest peak flow by drainage area raised to the 0.6 power. Units are cfs mi^{-2}.
[d] Not shown on Fig. 14; see Fig. 13 for location.
[e] Includes only the "unregulated" period of record prior to construction of major flood-control dams.
[f] Drainage area includes only the "unregulated" area downstream from Deerfield Dam.
[g] Drainage area includes only the "unregulated" area downstream from Pactola Dam.
[h] Includes only the "regulated" period of record after construction of major flood-control dams.
[i] From "paleoflood" investigation along Elk Creek (Harden et al. 2011), which documented four floods of ~75,000 to 83,000 cfs in the last 2000 yr. The largest flood was estimated as at least 83,000 cfs and occurred about 900 yr before present.

near the Limestone Plateau (Fig. 14, map numbers 1–8). Figure 15 has graphs showing the annual peak-flow time series for these eight stream gages. Figure 15a is for stream gage 06430770 (Spearfish Creek near Lead, drainage area = 65.0 mi^2) that is located just downstream from the confluence with East Spearfish Creek, and which measured the hydrologic response for the 5 August 2014 storm (Fig. 2). The largest peak flow for 25 yr of record for this site (181 cfs, Table 3) is about 50% smaller than the 5 August peak flow for the Keough Draw site with a drainage area of 1.0 mi^2. The normalized value for Keough Draw (340 cfs mi^{-2}) is about 23 times larger than the normalized value for stream gage 06430770 (14.8 cfs mi^{-2}). Little Spearfish Creek (stream gage 06430850, Fig. 15b) has peak-flow characteristics that are quite similar to those for stream gage 06430770. Despite smaller drainage area (27.8 mi^2), the largest peak-flow for Little Spearfish Creek (215 cfs, Table 3) is about 20% larger than for stream gage 06430700, which results in a normalized peak-flow value (29.2 cfs mi^{-2}) of about twice that of stream gage 06430770 (14.8 cfs mi^{-2}).

In contrast, the drainage area for nearby Annie Creek (stream gage 06430800) is much smaller (3.73 mi^2) and is located in a distinctly different hydrogeologic setting (Driscoll and Carter 2001) that is dominated by outcrops of low-permeability intrusive rocks (Table 3) along the steep western flank of Terry Peak. Annie Creek has five peak flows approaching or exceeding 100 cfs (Fig. 15c), closely resembling the largest values for the much larger Spearfish Creek near Lead (stream gage 06430770, 65.0 mi^2). The normalized peak-flow value for Annie Creek (123 cfs mi^{-2}) is about 4–8 times larger than for the two aforementioned Spearfish Creek stream gages (06430850 and 06430770).

Silver Creek (stream gage 06408850, Fig. 15d) is much farther south and is a tributary to Rapid Creek within low-permeability metamorphic rocks of Precambrian age (Driscoll and Carter 2001). For the primary period of record (1969–79), all peak-flow values were between 2 and 14 cfs; however, a special measurement was made to estimate a peak flow of 400 cfs following a unique high-elevation storm of 6–7 July 2008. Driscoll et al. (2010) provided additional documentation regarding that storm and the hydrologic response. The resulting normalized peak-flow value of 133 cfs mi^{-2} is similar to that of Annie Creek.

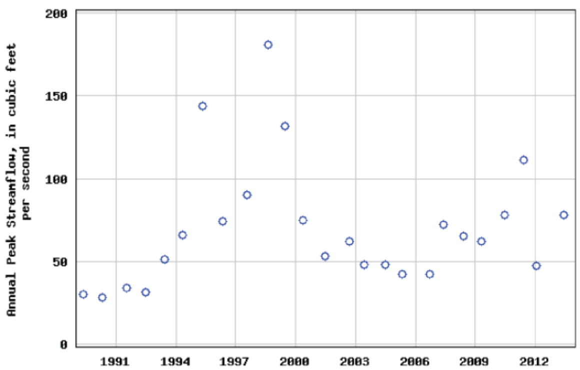
Of the four remaining high-elevation stream gages, Rhoads Fork (stream gage 06408700, Fig. 15e) and Cold Springs Creek (stream gage 06429500, Fig. 15f) have the smallest normalized peak-flow values of all listed sites (5.5 and 6.5 cfs mi^{-2}, respectively) and exemplify the minimal peak-flow characteristics for the Limestone Plateau hydrogeologic setting. Beaver Creek (stream gage 06392900, Fig. 15g) and Castle Creek (stream gage 06409000, Fig. 15h) are strongly affected by the Limestone Plateau hydrogeologic setting; however, their normalized peak-flow values are slightly elevated (38 and 81 cfs mi^{-2}, respectively) relative to the other high-elevation stream gages and are indicative of influences from other hydrogeology.

A second group in Table 3 for comparison with the Keough Draw and Ward Draw sites includes sites listed by Driscoll et al. (2010) or Harden et al. (2011). Site locations are shown by map numbers 9–33 on Fig. 14. These sites were selected to provide a broad representation for primary drainages throughout the Black Hills area. In general, most of the listed sites have relatively large normalized peak-flow values because of hydrogeologic settings that are much more conducive to generating large peak flows than the high-elevation Limestone Plateau area. The largest flow for nearly 50% of these sites occurred in 1972 from the exceptional rainstorm of 9–10 June (Schwarz et al. 1975), which had a storm footprint dwarfing that of all other documented storms for the Black Hills area (Driscoll et al. 2010).

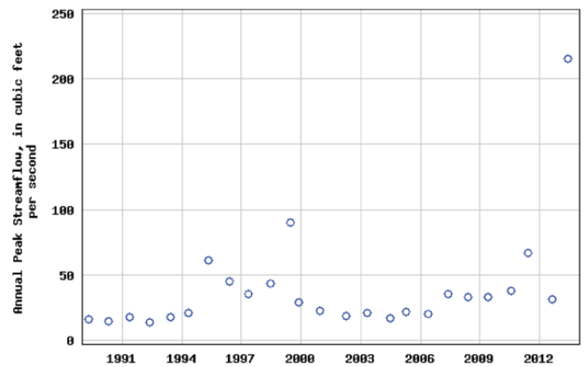
For stream gage 06400500 (Cheyenne River near Hot Springs, map number 9 on Fig. 14, drainage area = 8757 mi^2), the flow of 114,000 cfs is the largest flow ever measured for the Black Hills area (Driscoll et al. 2010). Although the “normalizing” exponent of 0.6 used by Sando et al. (2008) performs well for most applications, it cannot truly represent effects of exceptional thunderstorms, which typically can deliver very high rainfall intensities and volumes over relatively small areas. For example, the 1972 storm produced rainfall totals of ≥10 in over an area of about 76 mi^2 (Driscoll et al. 2010). From this standpoint, the normalized peak-flow value (491 cfs mi^{-2}) for this stream gage is exceptional.

For the next two stream gages in Table 3 (Fall River and Beaver Creek, map numbers 10 and 11), the largest peak flows of record occurred on the same date (4 September 1938). Given the relatively large drainage areas (136 and 127 mi^2, respectively), these peak flows are indicative of a storm with a particularly large footprint.

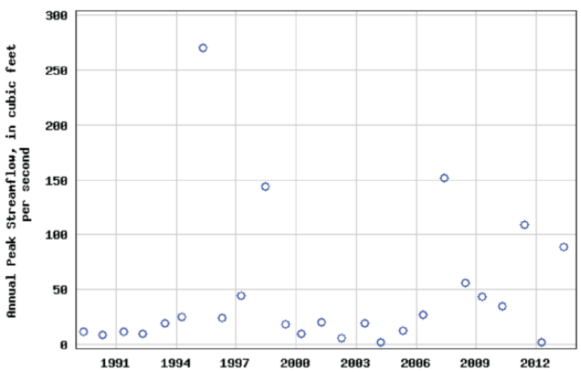
The next five stream gages in Table 3 (map numbers 12–16) are within the Battle Creek drainage, which includes a major tributary, Grace Coolidge



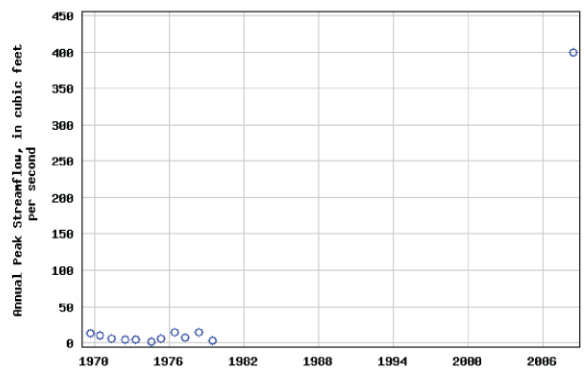
a) 06430770; Spearfish Creek near Lead, SD.



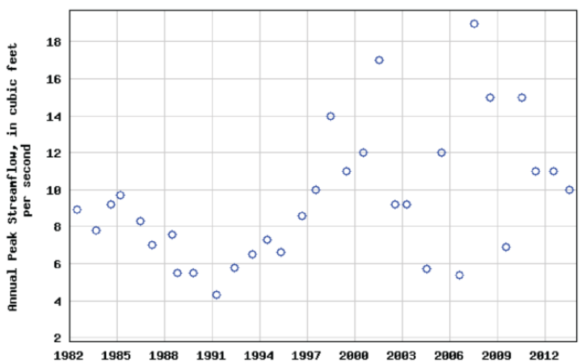
b) 06430850; Little Spearfish Creek near Lead, SD.



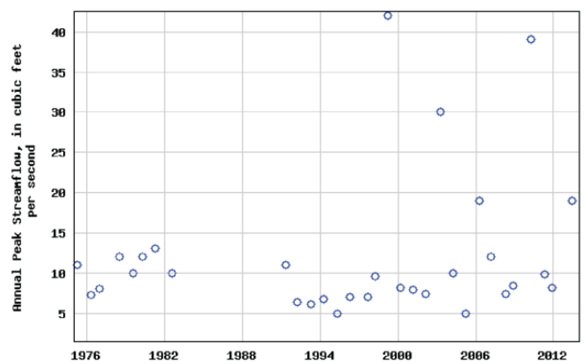
c) 06430800; Annie Creek near Lead, SD.



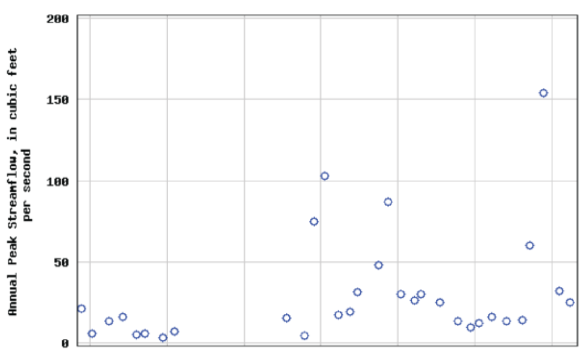
d) 06408850; Silver Creek near Rochford, SD.



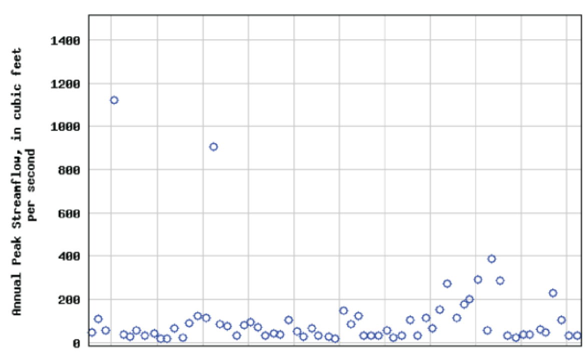
e) 06408700; Rhoads Fork near Rochford, SD.



f) 06429500; Cold Springs Creek at Buckhorn, WY.



g) 06392900; Beaver Creek at Mallo Camp, near Four Corners, WY.



h) 06409000; Castle Creek above Deerfield Reservoir near Hill City, SD.

Figure 15. Annual peak-flow time series plots for selected USGS stream gages. Refer to Table 3 and Fig. 14 for locations.

Creek, and all have especially large normalized peak-flow values. The peak flows for three of these sites (map numbers 14–16; all <1.0 mi^2) are from a storm of 17 August 2007 that delivered rainfall intensities exceeding that of the exceptional 1972 storm (Driscoll et al. 2010), which caused the large flows for the other two Battle Creek sites. The next two stream gages listed in Table 3 (map numbers 17–18) are within the Spring Creek drainage and have normalized peak-flow values from the 1972 storm that are smaller than the Battle Creek sites.

Stream gage 06410500 (map number 19, Rapid Creek above Pactola Reservoir) has the second smallest normalized peak-flow value of the final group (85 cfs mi^{-2}). The elevation for this site is higher than for most other sites in this group, and the western part of the drainage basin is within the Limestone Plateau. The largest flow of record occurred in 1965, as most of the drainage area was upstream from the heaviest parts of the 1972 storm, which caused especially large peak flows for three other stream gages farther downstream along Rapid Creek (map numbers 20–22). The normalized peak-flow value for stream gage 06414000 (Rapid Creek at Rapid City) is exceptional and results from full coverage of the historically large 1972 storm footprint over the drainage area of 93 mi^2 that is downstream from Pactola Reservoir.

The next three stream gages (map numbers 23–25) are along Boxelder Creek and Elk Creek, which had relatively large flows during 1972. The peak flow of 83,000 cfs for the Elk Creek "paleoflood" site was estimated from a paleoflood investigation (Harden et al. 2011) and is one of four extraordinary flows that have occurred within the last 2000 years. The floods recorded by geologic evidence along Elk Creek provide an important perspective regarding short-comings of our short-term observed records, relative to hydrologic extremes.

The last eight stream gages in Table 3 are located in the northern Black Hills. Of these, the largest normalized flow value is for stream gage 06437200 along Bear Butte Creek (map number 32), which had a large flow during 1972. The other seven sites have rather small normalized flow values, relative to most sites in the final group. The normalized value of 42 cfs mi^{-2} for stream gage 06429905 along Sand Creek (map number 26) is the smallest in the final group, for which the Limestone Plateau comprises a large part of a drainage area that includes a mix of hydrogeologic settings (Fig. 14, Table 3). The next smallest normalized value is for stream gage 06431500 along Spearfish Creek (map number 27), for which the Limestone Plateau also comprises a large part of a mixed drainage area. The normalized values for the other six sites also are fairly small, relative to most sites in Table 3.

The 5 August 2014 peak flows in Keough Draw and Ward Draw were quite small, compared to large flows that have been documented elsewhere in the Black Hills. The largest peak flows for many stream gages occurred during the exceptional flood of 1972. Relative to drainage area, some normalized peak flows are about an order of magnitude larger than for Keough Draw and Ward Draw. However, these are by far the largest known flows, relative to drainage area, for the Limestone Plateau area.

c. Context for future probability analyses

The data in Table 3 are consistent with interpretations of Driscoll et al. (2012), who provided qualitative perspectives on flash flood potential (Fig. 16) based on results of previous investigations. Sando et al. (2008) identified "suppressed" peak-flow characteristics for the Limestone Plateau area (Fig. 14), which coincides with the area of lowest flash flood potential (outlined in green on Fig. 16), where low relief and high infiltration capacities result in relatively small potential for generating direct runoff. Driscoll et al. (2010) analyzed the Black Hills climatology as a partial basis for hypothesizing that "generally increasing potential for exceptionally strong rain-producing thunderstorms in an easterly direction from the escarpment that lies along the eastern extent of the Limestone Plateau." The area of greatest perceived flash flood potential (outlined in red on Fig. 16) essentially coincides with the area of greatest perceived storm potential and is further enhanced by topographic factors—thin soils on steep slopes, with narrow canyons affording minimal potential for attenuation. An examination of historical storm and flood accounts by Driscoll et al. (2010) further informed the qualitative conclusions of Driscoll et al. (2012).

Quantification of extreme flood potential (recurrence intervals of ≥100 yr) requires probability analyses, which are hindered by relatively short-term hydroclimatic records. In Table 3, the longest gaged record is 76 yr (stream gage 06402500, map number 11). Harden et al. (2011) used geologic evidence of past extreme floods (paleofloods) to effectively extend record lengths and dramatically reduce statistical

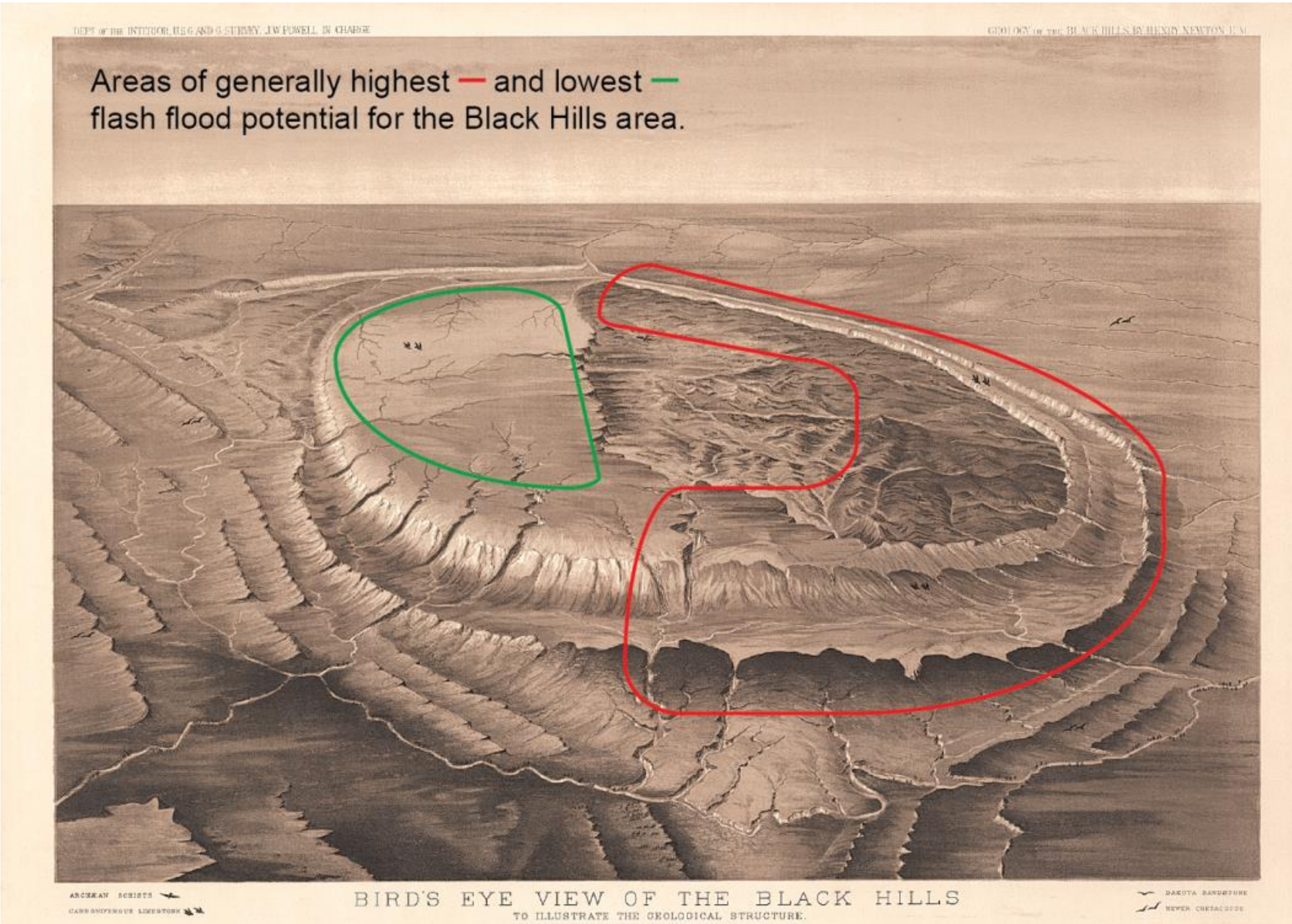


Figure 16. Generalized potential for flash flooding in the Black Hills area (Driscoll et al. 2012). The uplifted area essentially corresponds with the outer extent of the Inyan Kara Group, as shown on Fig. 14.

uncertainties in estimating recurrence intervals for extreme floods, such as those of 1972. That study provided evidence of floods much larger than those of 1972, such as those along Elk Creek (map number 24 in Table 3). Results were applicable only for specific areas along the flood-prone eastern flanks of the Black Hills, as geologic settings suitable for accumulating and preserving the necessary "slack-water flood deposits" unfortunately could not be found at high elevations.

Probability analyses for the high-elevation stream gages are especially challenging because of (1) especially short streamflow records, most typically only about 25–30 yr (Table 3), and (2) a relative dearth of high-flow events for the Limestone Plateau area, which likely owes to a combination of hydrogeologic and meteorological factors. It may be many years before sufficient lengths of hydroclimatic records can be collected to adequately address important uncertainties regarding the relative frequency of occurrence for extreme storm and flood events in the higher elevations of the Black Hills. Documentation of the 5 August 2014 meteorological circumstances and hydrologic response will by no means solve all immediate challenges, but will serve to provide important additional insights for improved understanding of the complex hydroclimatogy for this area.

5. Conclusion

A locally intense rainfall event (maximum measured = 4.5 in) produced an unusually large hydrologic response in the high-elevation northern Black Hills. Although long-term antecedent conditions were rather moist, some short-term dryness diminished the potential for flash flooding. Nevertheless, the hydrologic response to the 5 August 2014 rainfall was noteworthy in two small tributaries to East Spearfish Creek. Peak flows for Keough Draw (340 cfs from 1.0 mi^2) and Ward Draw (160 cfs from 2.9 mi^2) are about an order of magnitude smaller, relative to drainage area, than for peak flows for stream gages in more flood-prone parts of the Black Hills. However, these are by far the largest documented flows, relative to drainage area, for the high-elevation Limestone Plateau area.

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